Measurement of vertical bar V-cb vertical bar and the Form-Factor Slope in (B)over-bar -> Dl(-) (nu)over-bar(l) Decays in Events Tagged by a Fully Reconstructed B Meson

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Measurement of $|V_{cb}|$ and the Form-Factor Slope in $\bar{B} \to D\ell^- \bar{\nu}_\ell$ Decays in Events Tagged by a Fully Reconstructed B Meson

B. Aubert,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] M. Martinelli,[3a,3b] A. Palano,[3a,3b] M. Pappagallo,[3a,3b] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] M. Battaglia,[5] D. N. Brown,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. J. Asgeirsson,[8] B. G. Fulsom,[8] C. Hearty,[8] T. S. Mattison,[8] J. A. McKenna,[8] M. Barrett,[9] A. Khan,[9] A. Randle-Conde,[9] V. E. Blinov,[10] A. D. Bukin,[10,*] A. R. Buzykaev,[10] V. P. Druzhinin,[10] V. B. Golubev,[10] A. P. Onuchin,[10] S. I. Serednyakov,[10] Yu. I. Skovpen,[10] E. P. Solodov,[10] K. Yu. Todyshev,[10] M. Bondioli,[11] S. Curry,[11] I. Eschrich,[11] D. Kirkby,[11] A. J. Lankford,[11] P. Lund,[11] M. Mandelkern,[11] E. C. Martin,[11] D. P. Stoker,[11] H. Atmacan,[12] J. W. Gary,[12] F. Liu,[12] O. Long,[12] G. M. Vitug,[12] Z. Yasin,[12] L. Zhang,[12] V. Sharma,[13] C. Campagnari,[14] T. M. Hong,[14] D. Kovalskyi,[14] M. A. Mazur,[14] J. D. Richman,[14] T. W. Beck,[15] A. M. Eisner,[15] C. A. Heusch,[15] J. Kroseberg,[15] W. S. Lockman,[15] A. J. Martinez,[15] T. Schalk,[15] B. A. Schumm,[15] A. Seiden,[15] L. Wang,[15] L. O. Winstrom,[15] C. H. Cheng,[16] D. A. Doll,[16] B. Echenard,[16] F. Fang,[16] D. G. Hitlin,[16] I. Narsky,[16] T. Piatenko,[16] F. C. Porter,[16] R. Andreassen,[17] G. Mancinelli,[17] B. T. Meadows,[17] K. Mishra,[17] M. D. Sokoloff,[17] P. C. Bloom,[18] W. T. Ford,[18] A. Gaz,[18] J. F. Hirschauer,[18] M. Nagel,[18] U. Nauenberg,[18] J. G. Smith,[18] S. R. Wagner,[18] R. Ayad,[19,†] W. H. Toki,[19] R. J. Wilson,[19] E. Feltresi,[20] A. Hauke,[20] H. Jasper,[20] T. M. Karbach,[20] J. Merkel,[20] A. Petzold,[20] B. Spaan,[20] K. Wacker,[20] M. J. Kobel,[21] R. Nogowski,[21] K. R. Schubert,[21] R. Schwierz,[21] A. Volk,[21] D. Bernard,[22] E. Latour,[22] M. Verderi,[22] P. J. Clark,[23] S. Playfer,[23] J. E. Watson,[23] M. Andreotti,[24a,24b] D. Bettoni,[24a] C. Bozzi,[24a] R. Calabrese,[24a,24b] A. Cecchi,[24a,24b] G. Cibinetto,[24a,24b] E. Fioravanti,[24a,24b] P. Franchini,[24a,24b] E. Luppi,[24a,24b] M. Munerato,[24a,24b] M. Negrini,[24a,24b] A. Petrella,[24a,24b] L. Piemontese,[24a] V. Santoro,[24a,24b] R. Baldini-Ferroli,[25] A. Calcaterra,[25] R. de Sangro,[25] G. Finocchiaro,[25] S. Pacetti,[25] P. Patteri,[25] I. M. Peruzzi,[25,‡] M. Piccolo,[25] M. Rama,[25] A. Zallo,[25] R. Contri,[26a,26b] E. Guido,[26a] M. Lo Vetere,[26a,26b] M. R. Monge,[26a,26b] S. Passaggio,[26a] C. Patrignani,[26a,26b] E. Robutti,[26a] S. Tosi,[26a,26b] K. S. Chaisanguanthum,[27] M. Morii,[27] A. Adametz,[28] J. Marks,[28] S. Schenk,[28] U. Uwer,[28] F. U. Bernlochner,[29] V. Klose,[29] H. M. Lacker,[29] D. J. Bard,[30] P. D. Dauncey,[30] M. Tibbetts,[30] P. K. Behera,[31] M. J. Charles,[31] U. Mallik,[31] J. Cochran,[32] H. B. Crawley,[32] L. Dong,[32] V. Eyges,[32] W. T. Meyer,[32] S. Prell,[32] E. I. Rosenberg,[32] A. E. Rubin,[32] Y. Y. Gao,[33] A. V. Gritsan,[33] Z. J. Guo,[33] N. Arnaud,[34] J. Béquilleux,[34] A. D'Orazio,[34] M. Davier,[34] D. Derkach,[34] J. Firmino da Costa,[34] G. Grosdidier,[34] F. Le Diberder,[34] V. Lepeltier,[34] A. M. Lutz,[34] B. Malaescu,[34] S. Pruvot,[34] P. Roudeau,[34] M. H. Schune,[34] J. Serrano,[34] V. Sordini,[34,§] A. Stocchi,[34] G. Wormser,[34] D. J. Lange,[35] D. M. Wright,[35] I. Bingham,[36] J. P. Burke,[36] C. A. Chavez,[36] J. R. Fry,[36] E. Gabathuler,[36] R. Gamet,[36] D. E. Hutchcroft,[36] D. J. Payne,[36] C. Touramanis,[36] A. J. Bevan,[37] C. K. Clarke,[37] F. Di Lodovico,[37] R. Sacco,[37] M. Sigamani,[37] G. Cowan,[38] S. Paramesvaran,[38] A. C. Wren,[38] D. N. Brown,[39] C. L. Davis,[39] A. G. Denig,[40] M. Fritsch,[40] W. Gradl,[40] A. Hafner,[40] K. E. Alwyn,[41] D. Bailey,[41] R. J. Barlow,[41] G. Jackson,[41] G. D. Lafferty,[41] T. J. West,[41] J. I. Yi,[41] J. Anderson,[42] C. Chen,[42] A. Jawahery,[42] D. A. Roberts,[42] G. Simi,[42] J. M. Tuggle,[42] C. Dallapiccola,[43] E. Salvati,[43] S. Saremi,[43] R. Cowan,[44] D. Dujmic,[44] P. H. Fisher,[44] S. W. Henderson,[44] G. Sciolla,[44] M. Spitznagel,[44] R. K. Yamamoto,[44] M. Zhao,[44] P. M. Patel,[45] S. H. Robertson,[45] M. Schram,[45] A. Lazzaro,[46a,46b] V. Lombardo,[46a] F. Palombo,[46a,46b] S. Stracka,[46a,46b] J. M. Bauer,[47] L. Cremaldi,[47] R. Godang,[47,∥] R. Kroeger,[47] P. Sonnek,[47] D. J. Summers,[47] H. W. Zhao,[47] M. Simard,[48] P. Taras,[48] H. Nicholson,[49] G. De Nardo,[50a,50b] L. Lista,[50a] D. Monorchio,[50a,50b] G. Onorato,[50a,50b] C. Sciacca,[50a,50b] G. Raven,[51] H. L. Snoek,[51] C. P. Jessop,[52] K. J. Knoepfel,[52] J. M. LoSecco,[52] W. F. Wang,[52] L. A. Corwin,[53] K. Honscheid,[53] H. Kagan,[53] R. Kass,[53] J. P. Morris,[53] A. M. Rahimi,[53] J. J. Regensburger,[53] S. J. Sekula,[53] Q. K. Wong,[53] N. L. Blount,[54] J. Brau,[54] R. Frey,[54] O. Igonkina,[54] J. A. Kolb,[54] M. Lu,[54] R. Rahmat,[54] N. B. Sinev,[54] D. Strom,[54] J. Strube,[54] E. Torrence,[54] G. Castelli,[55a,55b] N. Gagliardi,[55a,55b] M. Margoni,[55a,55b] M. Morandin,[55a] M. Posocco,[55a] M. Rotondo,[55a] F. Simonetto,[55a,55b] R. Stroili,[55a,55b] C. Voci,[55a,55b] P. del Amo Sanchez,[56] E. Ben-Haim,[56] G. R. Bonneaud,[56] H. Briand,[56] J. Chauveau,[56] O. Hamon,[56] Ph. Leruste,[56] G. Marchiori,[56] J. Ocariz,[56] A. Perez,[56] J. Prendki,[56] S. Sitt,[56] L. Gladney,[57] M. Biasini,[58a,58b] E. Manoni,[58a,58b] C. Angelini,[59a,59b] G. Batignani,[59a,59b] S. Bettarini,[59a,59b] G. Calderini,[59a,59b,¶] M. Carpinelli,[59a,59b,**] A. Cervelli,[59a,59b] F. Forti,[59a,59b] M. A. Giorgi,[59a,59b] A. Lusiani,[59a,59c] M. Morganti,[59a,59b] N. Neri,[59a,59b] E. Paoloni,[59a,59b] G. Rizzo,[59a,59b] J. J. Walsh,[59a] D. Lopes Pegna,[60] C. Lu,[60] J. Olsen,[60] A. J. S. Smith,[60] A. V. Telnov,[60] F. Anulli,[61a] E. Baracchini,[61a,61b] G. Cavoto,[61a] R. Faccini,[61a,61b] F. Ferrarotto,[61a] F. Ferroni,[61a,61b] M. Gaspero,[61a,61b] P. D. Jackson,[61a] L. Li Gioi,[61a] M. A. Mazzoni,[61a] S. Morganti,[61a] G. Piredda,[61a] F. Renga,[61a,61b] C. Voena,[61a] M. Ebert,[62] T. Hartmann,[62] H. Schröder,[62] R. Waldi,[62] T. Adye,[63] B. Franek,[63]

E. O. Olaiya,[63] F. F. Wilson,[63] S. Emery,[64] L. Esteve,[64] G. Hamel de Monchenault,[64] W. Kozanecki,[64] G. Vasseur,[64] Ch. Yèche,[64] M. Zito,[64] M. T. Allen,[65] D. Aston,[65] R. Bartoldus,[65] J. F. Benitez,[65] R. Cenci,[65] J. P. Coleman,[65] M. R. Convery,[65] J. C. Dingfelder,[65] J. Dorfan,[65] G. P. Dubois-Felsmann,[65] W. Dunwoodie,[65] R. C. Field,[65] M. Franco Sevilla,[65] A. M. Gabareen,[65] M. T. Graham,[65] P. Grenier,[65] C. Hast,[65] W. R. Innes,[65] J. Kaminski,[65] M. H. Kelsey,[65] H. Kim,[65] P. Kim,[65] M. L. Kocian,[65] D. W. G. S. Leith,[65] S. Li,[65] B. Lindquist,[65] S. Luitz,[65] V. Luth,[65] H. L. Lynch,[65] D. B. MacFarlane,[65] H. Marsiske,[65] R. Messner,[65,*] D. R. Muller,[65] H. Neal,[65] S. Nelson,[65] C. P. O'Grady,[65] I. Ofte,[65] M. Perl,[65] B. N. Ratcliff,[65] A. Roodman,[65] A. A. Salnikov,[65] R. H. Schindler,[65] J. Schwiening,[65] A. Snyder,[65] D. Su,[65] M. K. Sullivan,[65] K. Suzuki,[65] S. K. Swain,[65] J. M. Thompson,[65] J. Va'vra,[65] A. P. Wagner,[65] M. Weaver,[65] C. A. West,[65] W. J. Wisniewski,[65] M. Wittgen,[65] D. H. Wright,[65] H. W. Wulsin,[65] A. K. Yarritu,[65] C. C. Young,[65] V. Ziegler,[65] X. R. Chen,[66] H. Liu,[66] W. Park,[66] M. V. Purohit,[66] R. M. White,[66] J. R. Wilson,[66] P. R. Burchat,[67] A. J. Edwards,[67] T. S. Miyashita,[67] S. Ahmed,[68] M. S. Alam,[68] J. A. Ernst,[68] B. Pan,[68] M. A. Saeed,[68] S. B. Zain,[68] A. Soffer,[69] S. M. Spanier,[70] B. J. Wogsland,[70] R. Eckmann,[71] J. L. Ritchie,[71] A. M. Ruland,[71] C. J. Schilling,[71] R. F. Schwitters,[71] B. C. Wray,[71] B. W. Drummond,[72] J. M. Izen,[72] X. C. Lou,[72] F. Bianchi,[73a,73b] D. Gamba,[73a,73b] M. Pelliccioni,[73a,73b] M. Bomben,[74a,74b] L. Bosisio,[74a,74b] C. Cartaro,[74a,74b] G. Della Ricca,[74a,74b] L. Lanceri,[74a,74b] L. Vitale,[74a,74b] V. Azzolini,[75] N. Lopez-March,[75] F. Martinez-Vidal,[75] D. A. Milanes,[75] A. Oyanguren,[75] J. Albert,[76] Sw. Banerjee,[76] B. Bhuyan,[76] H. H. F. Choi,[76] K. Hamano,[76] G. J. King,[76] R. Kowalewski,[76] M. J. Lewczuk,[76] I. M. Nugent,[76] J. M. Roney,[76] R. J. Sobie,[76] T. J. Gershon,[77] P. F. Harrison,[77] J. Ilic,[77] T. E. Latham,[77] G. B. Mohanty,[77] E. M. T. Puccio,[77] H. R. Band,[78] X. Chen,[78] S. Dasu,[78] K. T. Flood,[78] Y. Pan,[78] R. Prepost,[78] C. O. Vuosalo,[78] and S. L. Wu[78]

(*BaBar* Collaboration)

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3a]*INFN Sezione di Bari, Dipartimento di Fisica, I-70126 Bari, Italy*
[3b]*Università di Bari, I-70126 Bari, Italy*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[9]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[10]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[11]*University of California at Irvine, Irvine, California 92697, USA*
[12]*University of California at Riverside, Riverside, California 92521, USA*
[13]*University of California at San Diego, La Jolla, California 92093, USA*
[14]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[15]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[16]*California Institute of Technology, Pasadena, California 91125, USA*
[17]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[18]*University of Colorado, Boulder, Colorado 80309, USA*
[19]*Colorado State University, Fort Collins, Colorado 80523, USA*
[20]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[21]*Technische Universität Dresden, Institut für Kern-und Teilchenphysik, D-01062 Dresden, Germany*
[22]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[23]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[24a]*INFN Sezione di Ferrara, Dipartimento di Fisica, I-44100 Ferrara, Italy*
[24b]*Università di Ferrara, I-44100 Ferrara, Italy*
[25]*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[26a]*INFN Sezione di Genova, Dipartimento di Fisica, I-16146 Genova, Italy*
[26b]*Università di Genova, I-16146 Genova, Italy*
[27]*Harvard University, Cambridge, Massachusetts 02138, USA*
[28]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[29]*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstrasse 15, D-12489 Berlin, Germany*
[30]*Imperial College London, London, SW7 2AZ, United Kingdom*
[31]*University of Iowa, Iowa City, Iowa 52242, USA*

[32]Iowa State University, Ames, Iowa 50011-3160, USA
[33]Johns Hopkins University, Baltimore, Maryland 21218, USA
[34]Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 Orsay Cedex, France
[35]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[36]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[37]Queen Mary, University of London, London, E1 4NS, United Kingdom
[38]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[39]University of Louisville, Louisville, Kentucky 40292, USA
[40]Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
[41]University of Manchester, Manchester M13 9PL, United Kingdom
[42]University of Maryland, College Park, Maryland 20742, USA
[43]University of Massachusetts, Amherst, Massachusetts 01003, USA
[44]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[45]McGill University, Montréal, Québec, Canada H3A 2T8
[46a]INFN Sezione di Milano, Dipartimento di Fisica, I-20133 Milano, Italy
[46b]Università di Milano, I-20133 Milano, Italy
[47]University of Mississippi, University, Mississippi 38677, USA
[48]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
[49]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[50a]INFN Sezione di Napoli, Dipartimento di Scienze Fisiche, I-80126 Napoli, Italy
[50b]Università di Napoli Federico II, I-80126 Napoli, Italy
[51]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[52]University of Notre Dame, Notre Dame, Indiana 46556, USA
[53]Ohio State University, Columbus, Ohio 43210, USA
[54]University of Oregon, Eugene, Oregon 97403, USA
[55a]INFN Sezione di Padova, Dipartimento di Fisica, I-35131 Padova, Italy
[55b]Università di Padova, I-35131 Padova, Italy
[56]Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
[57]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[58a]INFN Sezione di Perugia, Dipartimento di Fisica, I-06100 Perugia, Italy
[58b]Università di Perugia, I-06100 Perugia, Italy
[59a]INFN Sezione di Pisa, Dipartimento di Fisica, I-56127 Pisa, Italy
[59b]Università di Pisa, I-56127 Pisa, Italy
[59c]Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy
[60]Princeton University, Princeton, New Jersey 08544, USA
[61a]INFN Sezione di Roma, Dipartimento di Fisica, I-00185 Roma, Italy
[61b]Università di Roma La Sapienza, I-00185 Roma, Italy
[62]Universität Rostock, D-18051 Rostock, Germany
[63]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[64]CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
[65]SLAC National Accelerator Laboratory, Stanford, California 94309 USA
[66]University of South Carolina, Columbia, South Carolina 29208, USA
[67]Stanford University, Stanford, California 94305-4060, USA
[68]State University of New York, Albany, New York 12222, USA
[69]Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
[70]University of Tennessee, Knoxville, Tennessee 37996, USA
[71]University of Texas at Austin, Austin, Texas 78712, USA
[72]University of Texas at Dallas, Richardson, Texas 75083, USA
[73a]INFN Sezione di Torino, Dipartimento di Fisica Sperimentale, I-10125 Torino, Italy
[73b]Università di Torino, I-10125 Torino, Italy
[74a]INFN Sezione di Trieste, Dipartimento di Fisica, I-34127 Trieste, Italy
[74b]Università di Trieste, I-34127 Trieste, Italy
[75]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[76]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[77]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[78]University of Wisconsin, Madison, Wisconsin 53706, USA

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We present a measurement of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ and the form-factor slope ρ^2 in $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decays based on 460×10^6 $B\bar{B}$ events recorded at the $\Upsilon(4S)$ resonance with the *BABAR* detector. $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decays are selected in events in which a hadronic decay of the second B meson is fully reconstructed. We measure $\mathcal{B}(B^- \to D^0\ell^- \bar{\nu}_\ell)/\mathcal{B}(B^- \to X\ell^- \bar{\nu}_\ell) = (0.255 \pm 0.009 \pm 0.009)$ and $\mathcal{B}(\bar{B}^0 \to D^+\ell^- \bar{\nu}_\ell)/\mathcal{B}(\bar{B}^0 \to X\ell^- \bar{\nu}_\ell) = (0.230 \pm 0.011 \pm 0.011)$, along with the differential decay distribution in $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decays. We then determine $\mathcal{G}(1)|V_{cb}| = (42.3 \pm 1.9 \pm 1.4) \times 10^{-3}$ and $\rho^2 = 1.20 \pm 0.09 \pm 0.04$, where $\mathcal{G}(1)$ is the hadronic form factor at the point of zero recoil.

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In the standard model (SM) of electroweak interactions, the rate of the semileptonic $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decay is proportional to the square of the Cabibbo-Kobayashi-Maskawa (CKM) [1] matrix element $|V_{cb}|$, which is a measure of the weak coupling of the b to the c quark. The length of the side of the unitarity triangle opposite to the well-measured angle β is proportional to $|V_{ub}/V_{cb}|$, making the determination of $|V_{cb}|$ an important test of the SM description of CP violation. In addition, imprecise knowledge of $|V_{cb}|$ is a significant uncertainty limiting comparison of CP violation measurements in K-meson decays with those in B-meson decays [2].

$|V_{cb}|$ has been extracted from inclusive semileptonic B decays [3] and exclusive decays $\bar{B} \to D\ell^- \bar{\nu}_\ell$ and $\bar{B} \to D^*\ell^- \bar{\nu}_\ell$ [4]. The results rely on different QCD calculations. For inclusive decays, the decay rate is predicted by an expansion in inverse powers of the b-quark mass and in terms of the strong coupling constant α_S, while exclusive decays are expressed in terms of form factors with a normalization taken from Heavy Quark Symmetry and nonperturbative QCD calculations. The theoretical uncertainties of these two approaches are independent, and the measurements have, to a large extent, uncorrelated statistical and systematic uncertainties. This makes the comparison of $|V_{cb}|$ from inclusive and exclusive decays a powerful test of our understanding of semileptonic decays. The most recent results differ by more than 2 standard deviations, with the error on the exclusive measurements larger by a factor >2 [5]. The $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decay is to a large extent complementary to the $\bar{B} \to D^*\ell^- \bar{\nu}_\ell$, which depends on three form factors and therefore requires a full angular analysis. Improvements in the measurements of the exclusive decay rates are highly desirable, in particular, for $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decays where, at present, the experimental uncertainties dominate. Studies of $\bar{B} \to D\ell^- \bar{\nu}_\ell$ decays have previously been reported by the Belle [6], CLEO [7], ALEPH [8], and *BABAR* [4] Collaborations.

The $\bar{B} \to D\ell^- \bar{\nu}_\ell$ differential decay rate $d\Gamma_D/dw$ [9] depends on the hadronic matrix element describing strong-interaction effects in $\bar{B} \to D$ transitions. In the limit of very small lepton masses ($\ell = e$ or μ), their effect can be parametrized by a single form factor $\mathcal{G}(w)$:

$$\frac{d\Gamma_D}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3\hbar} M_D^3 (M_B + M_D)^2 (w^2 - 1)^{3/2} \mathcal{G}^2(w), \quad (1)$$

where G_F is the Fermi coupling constant, and M_B and M_D are the masses of the B and D mesons, respectively. The variable w denotes the product of the B and D meson 4-velocities V_B and V_D, $w = V_B \cdot V_D = (M_B^2 + M_D^2 - q^2)/(2M_B M_D)$, where $q^2 \equiv (p_B - p_D)^2$, and p_B and p_D are the 4-momenta of the B and D mesons.

In the limit of infinite heavy quark masses, $\mathcal{G}(w)$ coincides with the Isgur-Wise function [10]. This function is normalized to unity at zero recoil, where q^2 is maximum. Corrections to the heavy quark limit have been calculated based on unquenched [11] and quenched lattice QCD [12]. Thus $|V_{cb}|$ can be extracted by extrapolating the differential decay rate to $w = 1$. To reduce the uncertainties associated with this extrapolation, constraints on the shape of the form factor are necessary. Several functional forms have been proposed [13]. We adopt the parametrization suggested in Ref. [14], where the nonlinear dependence of the form factor on w is expressed in terms of a single shape parameter, the form-factor slope ρ^2. In Ref. [12] the form factor $\mathcal{G}(w)$ has been computed at a few points above the zero recoil limit, up to $w = 1.2$. This allows us to extract $|V_{cb}|$ in a region where the rate is much larger, avoiding the large extrapolation to $w = 1$.

In this Letter, we present a measurement of $d\Gamma_D/dw$ for $\bar{B}^0 \to D^+\ell^- \bar{\nu}_\ell$ and $B^- \to D^0\ell^- \bar{\nu}_\ell$ decays from which we extract $\mathcal{G}(w)|V_{cb}|$ at $w = 1.0$ and at few points with $w > 1.0$. The analysis is based on data collected with the *BABAR* detector [15] at the PEP-II asymmetric-energy e^+e^- storage rings. The data consist of 417 fb^{-1} recorded at the $\Upsilon(4S)$ resonance, corresponding to approximately 460×10^6 $B\bar{B}$ pairs. An additional sample of 40 fb^{-1}, collected at a center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$ resonance, is used to study background from $e^+e^- \to f\bar{f}(f = u, d, s, c, \tau)$ continuum events. We also use samples of GEANT4 Monte Carlo (MC) simulated events that correspond to about three times the data sample size. The simulation models $\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell$ decays using calculations based on heavy quark effective theory (HQET) [14], $\bar{B} \to D^{**}(\to D^{(*)}\pi)\ell^- \bar{\nu}_\ell$ decays using the ISGW2 model [16], and nonresonant $\bar{B} \to D^{(*)}\pi\ell^- \bar{\nu}_\ell$ decays using the Goity-Roberts model [17]. The MC simulation includes radiative effects such as bremsstrahlung in the detector material and final-state radiation modeled by PHOTOS [18].

Semileptonic decays are selected in $B\bar{B}$ events in which a hadronic decay of the second B meson ($B_{\rm tag}$) is fully reconstructed, following the same criteria used in Ref. [19] and briefly summarized here. We first reconstruct the semileptonic decay selecting a lepton with momentum in the c.m. frame $p^*_\ell > 0.6$ GeV and a well-reconstructed D^0/D^+ candidate with the correct charge correlation with the lepton. Then we reconstruct the $B_{\rm tag}$ decays in about 1000 different charmed hadronic modes $\bar{B} \to D^{(*)}Y$ where Y represents a combination of $\pi^\pm$, π^0, $K^\pm$, or K^0_S [20]. The kinematic consistency of a $B_{\rm tag}$ candidate with a B meson decay is evaluated requiring $5.27 < m_{\rm ES} \equiv \sqrt{s/4 - (p^*_B)^2} < 5.29$ GeV, where $\sqrt{s}$ is the total c.m. energy, and p^*_B and E^*_B denote the momentum and energy of the $B_{\rm tag}$ candidate in the c.m. frame.

Semileptonic B decays are identified by their missing mass squared, $m^2_{\rm miss} = [p_{\Upsilon(4S)} - p_{B_{\rm tag}} - p_D - p_\ell]^2$, calculated from the measured particles 4-momenta. For correctly reconstructed signal events, the only missing particle is the neutrino and $m^2_{\rm miss}$ peaks at zero. Other semileptonic B decays, like $\bar{B} \to D^{(*,**)}\ell^-\bar{\nu}_\ell$, where at least one particle is not reconstructed (feed-down), yield larger values of $m^2_{\rm miss}$.

We measure $\mathcal{G}(1)|V_{\rm cb}|$ and the form-factor slope ρ^2 by a fit to the w distribution. We examine the data and MC events in ten equal-size w bins in the interval $1 < w < 1.6$. Since the B momentum is known from the fully reconstructed $B_{\rm tag}$ in the same event, w is reconstructed with good precision, namely, to ~ 0.01, which corresponds to about 2% of the full kinematic range.

The $\bar{B} \to D\ell^-\bar{\nu}_\ell$ signal yield in each bin of w is obtained from the $m^2_{\rm miss}$ distribution in data by an extended binned maximum likelihood fit [21]. We assume that the data sample is described by contributions from four different sources: $\bar{B} \to D\ell^-\bar{\nu}_\ell$ signal events, feed-down from other semileptonic B decays, combinatorial $B\bar{B}$ and continuum background, and fake lepton events (mostly from hadronic B decays with hadrons misidentified as leptons). The probability density functions (PDFs) are derived from the MC predictions for the different semileptonic B decay $m^2_{\rm miss}$ distributions. We use the off-peak data to provide the continuum background normalization. The shape of the continuum background distribution predicted by the MC simulation is consistent with that obtained from the off-peak data. The measured $m^2_{\rm miss}$ distributions are compared with the results of the fits for two different w intervals in Fig. 1.

We perform a least-squares fit to the observed signal yields in the ten bins of w. We minimize a χ^2 defined as

$$\chi^2 = \sum_{i=1}^{10} \frac{(N^i_{\rm data} - \sum_{j=1}^{N^i_{\rm MC}} W^i_j)^2}{(\sigma^i_{\rm data})^2 + \sum_{j=1}^{N^i_{\rm MC}} W^{i2}_j}, \qquad (2)$$

where the index i refers to the w bin and the index j runs over all MC events in bin i; $N^i_{\rm data}$ is the observed number of signal events found in the ith bin and $\sigma^i_{\rm data}$ the corresponding uncertainty. The expected signal yields are calculated at each step of the minimization from the reweighted sum of $N^i_{\rm MC}$ simulated events. Each weight is the product of two terms: $W^i_j = W^{\mathcal{L}} \times W^{i,\rm theo}_j$, where $W^{\mathcal{L}}$ is an overall fixed scale factor, which accounts for the relative integrated luminosity of the data and signal MC events, and $W^{i,\rm theo}_j$ is computed using the true w value of the event j and depends on $\mathcal{G}(1)|V_{\rm cb}|$ and ρ^2, which are free parameters determined in the fit that are recalculated at each step of the minimization.

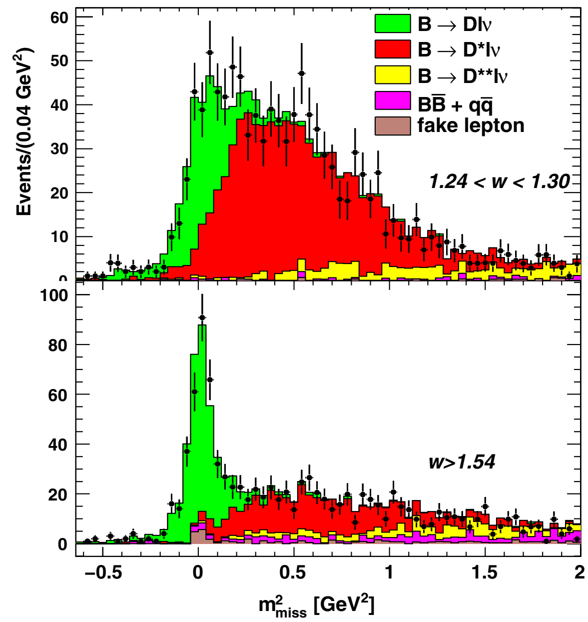

FIG. 1 (color online). Fit to the $m^2_{\rm miss}$ distribution in two different w intervals for $B^- \to D^0\ell^-\bar{\nu}_\ell$: the data (points with error bars) are compared to the results of the overall fit (sum of the solid histograms). The PDFs for the different fit components are stacked in the order shown in the legend.

We first fit the w distributions for the charged and neutral $\bar{B} \to D\ell^-\bar{\nu}_\ell$ samples separately and then perform a fit to the combined $\bar{B} \to D\ell^-\bar{\nu}_\ell$ sample. In Fig. 2, we show the comparison between the data and the fit results for the combined sample. The measured values of $\mathcal{G}(1)|V_{\rm cb}|$ and ρ^2, with the corresponding correlation $\rho_{\rm corr}$ obtained from the fit, are reported in Table I. The branching fraction is derived by integrating Eq. (1) and dividing by the appropriate B-meson lifetime.

In order to reduce the systematic uncertainty on the measurement of $\mathcal{G}(1)|V_{\rm cb}|$ and the branching fractions, we normalize the exclusive signal yield to the yield of inclusive semileptonic decays, $\bar{B} \to X\ell^-\bar{\nu}_\ell$, in events tagged by a fully reconstructed hadronic B decay. The inclusive $\bar{B} \to X\ell^-\bar{\nu}_\ell$ decays are selected by identifying one charged lepton with $p^*_\ell > 0.6$ GeV and the charge expected based on the $B_{\rm tag}$ decay. In the case of multiple

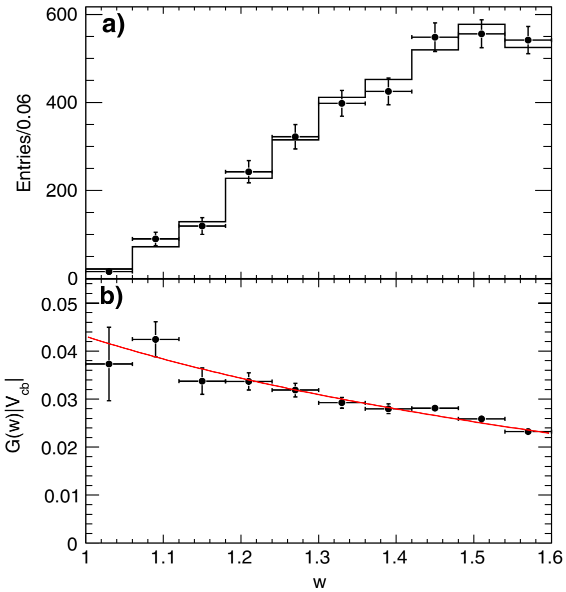

FIG. 2 (color online). (a) Signal yield w distribution obtained summing $B^- \to D^0\ell^-\bar{\nu}_\ell$ and $\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell$ events. The data (●) are compared to the results of the overall fit (histogram). (b) $\mathcal{G}(w)|V_{cb}|$ distribution corrected for the reconstruction efficiency, with the fit result superimposed.

$B_{\rm tag}$ candidates in an event, we select the decay mode with the highest purity, estimated from the MC prediction for the fraction of true decays in the $m_{\rm ES}$ signal region. Background components that peak in the $m_{\rm ES}$ signal region include cascade B meson decays, for which the lepton does not come directly from the B, and hadronic decays; they are subtracted using the corresponding MC predictions. The $\bar{B} \to X\ell^-\bar{\nu}_\ell$ yield is obtained from a maximum likelihood fit to the $m_{\rm ES}$ distribution of the $B_{\rm tag}$ candidates, as described in Ref. [19]. The fit yields $(198.9 \pm 1.6) \times 10^3$ events for the $B^- \to X\ell^-\bar{\nu}_\ell$ sample and $(116.3 \pm 1.0) \times 10^3$ events for the $\bar{B}^0 \to X\ell^-\bar{\nu}_\ell$ sample. The corresponding reconstruction efficiencies, including the $B_{\rm tag}$ reconstruction, are 0.39% and 0.25%, respectively. We investigated numerous sources of systematic uncertainties, whose contributions are listed in Ref. [22]. The largest uncertainties are due to differences in the efficiency of the $B_{\rm tag}$ selection between the exclusive $\bar{B} \to D\ell^-\bar{\nu}_\ell$ and inclusive $\bar{B} \to X\ell^-\bar{\nu}_\ell$ decays (a relative 1.5% systematic uncertainty on $|V_{cb}|$), the $\bar{B} \to D\ell^-\bar{\nu}_\ell$ fit procedure (1.3%), and the uncertainties on the branching fractions of the reconstructed D decay modes and $\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ decays (1.1%). The uncertainties due to the detector simulation are established by varying, within bounds given by data control samples, the tracking efficiency of all charged tracks (0.7%), the calorimeter efficiency (0.9%), and the lepton identification efficiency (0.9%). We evaluate the systematic uncertainties associated with the MC simulation of various signal and background processes: photon conversion and π^0 Dalitz decay, B cascade decay contamination (0.8%), and flavor cross feed (0.2%). The uncertainty arising from radiative corrections (0.1%) is studied by comparing the standard results with those obtained when PHOTOS is not used. We take 30% of the difference as a conservative systematic uncertainty. We vary the $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ form factors (0.4%) within their measured uncertainties [4] and use a HQET parametrization [23] to describe $\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ decays (0.3%). We evaluate an uncertainty associated with the $\bar{B} \to X\ell^-\bar{\nu}_\ell$ fitting procedure (0.8%) and with the absolute branching fraction $\mathcal{B}(\bar{B} \to X\ell^-\bar{\nu}_\ell)$ used for the normalization (0.8%).

From the fit to the combined $\bar{B} \to D\ell^-\bar{\nu}_\ell$ sample, we measure $\mathcal{G}(1)|V_{cb}| = (42.3 \pm 1.9 \pm 1.4) \times 10^{-3}$. Using an unquenched lattice calculation [11], corrected by a factor of 1.007 for QED effects, we obtain $|V_{cb}| = (39.2 \pm 1.8 \pm 1.3 \pm 0.9_{\rm FF}) \times 10^{-3}$, where the third error is due to the theoretical uncertainty in $\mathcal{G}(1)$. As an alternative, we use a quenched lattice calculation based on the step scaling method (SSM) [12] and obtain $|V_{cb}| = (40.9 \pm 1.8 \pm 1.4 \pm 0.7_{\rm FF}) \times 10^{-3}$. The authors of [12] report the lattice determination of $\mathcal{G}(w)$ for finite momentum transfer. Although quenched, this calculation allows the extraction of $|V_{cb}|$ avoiding the large extrapolation to $w = 1$. For example, from a linear interpolation around $w = 1.2$, we obtain $|V_{cb}| = (40.7 \pm 1.3 \pm 1.4 \pm 1.0_{\rm FF}) \times 10^{-3}$. We re-

TABLE I. Fit results for each sample. The last column reports the result of the $\bar{B}^0/B^-$ combined fit (here $\mathcal{B}$ refers to $\bar{B}^0$ decays). We also report signal yields and reconstruction efficiencies integrated over the full w range. Absolute branching fractions (last row) are derived from relative branching fractions using $\mathcal{B}(B \to X\ell^-\bar{\nu}_\ell)$ from Ref. [5].

	$B^- \to D^0\ell^-\bar{\nu}_\ell$	$\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell$	$\bar{B} \to D\ell^-\bar{\nu}_\ell$
$\mathcal{G}(1)\lvert V_{cb}\rvert \cdot 10^3$	$41.0 \pm 2.1 \pm 1.3$	$44.9 \pm 3.2 \pm 1.6$	$42.3 \pm 1.9 \pm 1.4$
ρ^2	$1.14 \pm 0.11 \pm 0.04$	$1.29 \pm 0.14 \pm 0.05$	$1.20 \pm 0.09 \pm 0.04$
$\rho_{\rm corr}$	0.943	0.950	0.952
$\chi^2/{\rm ndf}$	3.4/8	5.6/8	9.9/18
Signal Yield	2147 ± 69	1108 ± 45	...
Reconstruction Efficiency	$(1.99 \pm 0.02) \times 10^{-4}$	$(1.09 \pm 0.02) \times 10^{-4}$	...
$\mathcal{B}(B \to D\ell^-\bar{\nu}_\ell)/\mathcal{B}(B \to X\ell^-\bar{\nu}_\ell)$	$(0.255 \pm 0.009 \pm 0.009)$	$(0.230 \pm 0.011 \pm 0.011)$	$(0.223 \pm 0.006 \pm 0.009)$
$\mathcal{B}(B \to D\ell^-\bar{\nu}_\ell)$	$(2.29 \pm 0.08 \pm 0.09)\%$	$(2.21 \pm 0.11 \pm 0.11)\%$	$(2.15 \pm 0.06 \pm 0.09)\%$

port our measurements of $\mathcal{G}(w)|V_{cb}|$ for $w > 1$ in Ref. [22]. The $|V_{cb}|$ measurement at $w > 1$ is affected by smaller uncertainties than the one extracted at $w = 1$.

The results presented here can be combined with a recent *BABAR* measurement [4]. We neglect the tiny statistical correlations among the two measurements and treat the systematic uncertainties as fully correlated. We obtain $\mathcal{G}(1)|V_{cb}| = (42.4 \pm 1.7) \times 10^{-3}$ and $\rho^2 = 1.18 \pm 0.06$, with a correlation coefficient of 0.89. We also obtain the branching fraction $\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell) = (2.15 \pm 0.08)\%$. The combined *BABAR* result (using the unquenched lattice calculation [11]) is $|V_{cb}| = (39.2 \pm 1.6 \pm 0.9_{FF}) \times 10^{-3}$, which is consistent with the measurement obtained from $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$, $|V_{cb}| = (38.6 \pm 0.9_{exp} \pm 1.0_{FF}) \times 10^{-3}$, decays, and also compatible with the inclusive determination of $|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}$ [5].

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*Deceased.

†Now at Temple University, Philadelphia, PA 19122, USA.

‡Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.

§Also with Università di Roma La Sapienza, I-00185 Roma, Italy.

‖Now at University of South Alabama, Mobile, AL 36688, USA.

¶Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France.

**Also with Università di Sassari, Sassari, Italy.

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